

CONVERTING TRIBOLOGY BASED CONDITION MONITORING INTO MEASURABLE MAINTENANCE RESULTS

by Ray Garvey and Grahame Fogel

Computational Systems Inc., 835 Innovation Drive, Knoxville, TN 37932

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Abstract: An effective industrial tribology program is much more than just oil analysis. Oil analysis reveals important information about the condition of machinery, lubricants, and contamination in the lubricants. Substantial savings are achievable through an effective oil analysis program. However, much greater benefits are achievable through a reliability based tribology program such as:

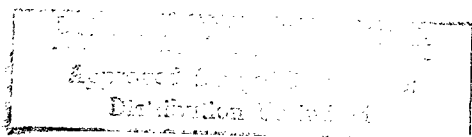
- improved capacity by avoiding breakdowns,
- known condition of equipment – thereby providing status of plant capacity,
- integrated with other condition monitoring technologies,
- improved overall indication of system health,
- employment of value based application of tribology technologies,
- achieved optimum selection of lubricants,
- application of contamination control and established cleanliness for systems,
- achieved machine and lubricant life extension,
- realized failure reduction through root cause analysis, and
- applied quality assurance for lubricants, filters, breathers, refurbishment, etc.

Key Words: Tribology, industrial oil analysis, benchmark, minilab, failure, abrasion, fatigue, adhesion, chemistry, contamination, wear, trivector, best practices.

Introduction: Tribology can be defined as the study of surfaces in relative motion. This multifaceted science addresses friction, lubrication, and wear, which are fundamental in nearly all mechanical systems. Each of these has major cost impacts within industrial plants.

For example, friction within mechanical systems directly translates into power loss. Lubrication costs include procurement, storage, filtration, installation, recycling, and disposal. Wear is the primary characteristic defining the end of life for plant machinery and leads to costs of maintenance, replacement, and production outage. Friction, lubrication, and wear are interactive and cannot be separated. A successful tribology program necessarily addresses all three elements from the perspective of their total cost to the industrial plant.

Oil analysis programs for industrial plants have been reported to save \$277,000 per year from extended oil drain intervals, avoided maintenance actions, and production uptime. The benefits from this more comprehensive approach have been documented as well over \$1,000,000 per year for very large plants and are classified as follows: 70% equipment failure, 20% lubricant procurement, 5% material handling, and 5% electrical power. See references 6, 9, 10, and 16.



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Industrial Fluid Analysis: Oil analysis of used lubricant and hydraulic fluid samples reveals deterioration or breakdown of the fluid, contamination of the system with water or particulate debris, and wear of the lubricated machinery. Oil analysis can be done on-site, by the reliability maintenance team, or off-site by a contracted fluid analysis laboratory. There are reasons, summarized in this report, why plants should do both of these.

In either case, it is important to understand that analysis of used lubricants is done to gain insights as the condition of the lubricant, the amount and types of contamination, and the health of the machine from which the fluid samples are taken. Substantial cost savings can be attributed to each of these factors.

The value of this information can only be realized if it can be collected and analyzed in a timely and organized manner. This is best done using a multilevel computer database that is logically organized based on proximity or types of machinery. Each database will include "oil routes" which identify a sequences for collecting oil and hydraulic fluid samples.

Further benefits are achieved by making more complete use of computerized tribology information as follows:

- samples scheduled automatically on condition,
- computerized trending and record keeping,
- knowledge based expert system assists with data interpretation,
- electronic link to lab,
- direct link with CMMS, and
- full integration of condition monitoring technologies.

In addition to analysis of used lubricants, the best tribology programs address the selection, procurement, storage, handling, monitoring, recycling, and disposal of these critical fluids as they are used throughout the plant. They initiate maintenance actions "on condition" rather than on a calendar basis whenever practical. They have management practices that effectively and efficiently collect tribology information, and support its influence within maintenance, operations, production. They take a proactive approach to maintenance, employing root cause failure analysis and contamination control measures.

Those plants following best practices for tribology will integrate the concept of profiles into their lubricant analysis activities. Each class of equipment has different loads, speeds, wear out and failure mechanisms from other classes. As such, each class fits into a profile for inspection, sampling, and analysis. This way, the analysis matches the requirements of the application.

Procurement Practices: Another "best practice" characteristic involves emphasis on the procurement of quality lubricants with ongoing quality assurance and quality control for lubricants, filters, and breathers. This is best done through a partnership relationship with lubricant and filter suppliers, understanding that the plant will continually review these products for their applicability and value.

Tribology as a part of Multi-Technology Condition Monitoring Team. Within the condition monitoring team, the vibration diagnosticians need to be equally comfortable with tribology, having a good understanding of lubrication technology. Best practice means incorporating preventive, proactive, predictive philosophies, utilizing full cost-benefit analysis to select the best combination of these. The underlying objective in each of these areas is the continuous reduction of lubrication costs, reduction of lubricant related maintenance costs, and increased production up-time.

Preventive Maintenance. Preventive maintenance includes interval based maintenance activities whose goal is to periodically inspect machines, add fluids, adjust components, replace parts, and overhaul machines based on the statistical likelihood that these actions are needed at just that interval. The interval for preventive maintenance is too soon if problems being addressed have not had sufficient time to develop. The interval is too late if failure modes have initiated and shortened design life of the machine. Since the latter situation is more serious than the first, and since the true condition of the machine is not known, preventive maintenance intervals are normally set at conservatively short periods.

Periodic inspections, oil sampling, and Calendar based oil change are three examples of tribology practices which fall into the category of preventive maintenance. The first two of these are intended to collect machine condition information which serve as a basis for proactive and predictive activities. The third, however, should be questioned. If the cost and impact of too frequent oil changes are small, then machine hours or Calendar days may be the most practical basis for initiating oil change work orders. However, Calendar based oil change is almost certainly being done either too soon or too late; too soon if the oil has remaining useful life, and too late if it is badly contaminated.

Proactive Maintenance. Proactive maintenance includes condition based maintenance activities which aimed at machine life extension as opposed to failure detection or breakdown prediction. This includes root cause failure analysis together with associated corrective measures. Proactive maintenance targets mechanisms leading to failure and eliminates them. When this is done properly, machine life can be doubled or even tripled.

Elimination (1) of deteriorated oil or (2) of excessive contamination or (3) of improper machine operating conditions (misalignment, imbalance, looseness, rub, etc.) are three good examples of tribology proactive maintenance practices. Independently, these conditions lead to physical wear and reduced machine life. When combined, these conditions are synergistic causing rapid machine deterioration.

Predictive Maintenance. Predictive maintenance includes condition based maintenance activities intended to non-intrusively predict remaining operational life of a mechanical system. This is typically done by monitoring the progression of failure from conditional (root cause) to incipient (initiated and in progress) to impending (significant damage) to precipitous (impaired) and finally to catastrophic (inoperable).

Tribology predictive maintenance practices view progressive states of wear deterioration to ascertain the remaining operational life in the machine. These include sampling and testing oil to measure and classify wear debris in the oil. The actual prediction of catastrophic breakdown of the machinery is normally best done using vibration analysis in conjunction with oil analysis.

Elimination of Root Causes of Failure. Machines can breakdown at any time, however, the reasons for breakdown typically fall into one of three time dependent categories: (1) start up, (2) random, and (3) wear out. Startup failures are those which occur within a short time after original equipment installation or within a short time after repair. Random failures occur at any time, regardless of machine life. Wear out failures determine the normal life of machinery and result from progressive deterioration of components which are subject to wear, aging, or chemical attack. After studying the causes and frequency of failure, the condition monitoring team can recommend investments be made in appropriate proactive measures to minimize or even eliminate these causes.

Startup Failures. Root causes of startup failures include improper assembly or installation, built in contamination, defective components, or machine design deficiencies. Most of these can be attributed to either the original equipment manufacturer or to the equipment installation team. Therefore, the controls to reduce startup failures are best implemented through improved contractual specifications:

- functional design specifications,
- startup and inspection before delivery,
- ISO cleanliness requirements,
- precision alignment and balance requirements,
- after installation startup and inspection, and
- cleanliness monitoring and removal of break-in wear debris.

Random Failures. Root causes of random failures can be elusive. The word random implies that one cannot find a common mode of systematic failure. Nonetheless, all failures have causes; and even when the causes are isolated and unusual, one can normally find contributing factors which can be minimized or eliminated. Failures tend to be synergistic. This is to say that two independent causes combined together are much worse than either one independently. It is reasonable to expect that when practices implemented to minimize both start up and wear out failure modes, then random failure modes will also be greatly reduced.

Wear Out Failures. Root causes of wear out failure include a synergistic combination of the environment, mechanical loads, and surface chemistry. Environmental factors affecting machine life include heat, dust, and water contamination. Mechanical loads can be acceptable or excessive, depending on machine operation, balance, shaft alignment, etc. Surface chemistry for oil wetted surfaces can be benign or under chemical attack, depending on the condition of the lubricant and presence of corrosive fluid contamination.

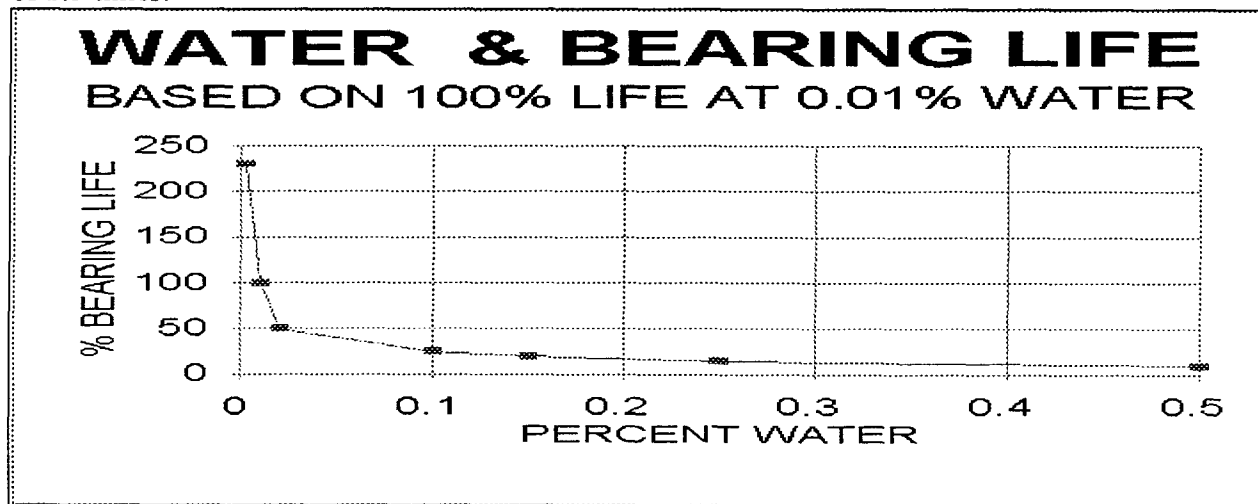
The combined effect of these environment/machine/chemistry factors results in physical wear. The following list shows seven basic lubricated wear mechanisms listed in percentage order:

- abrasive wear due to particulate contamination (46%),
- fatigue wear due to cyclic loading (17%),
- adhesive wear due to machine design tolerances (13%),
- corrosive wear due to contamination with moisture and air (9%),
- fretting wear due to chemical attack combined with oscillating motion (9%)
- erosive wear due to particulate contaminants (6%), and
- cavitation wear due to implosion of bubbles (<1%).

Principle Root Causes of Failure. There are seven principal root causes failure which promote wear in mechanical systems. An effective tribology program will take action to control the impact that each of these has, particularly on critical plant machinery.

- fluid contamination,
- fluid leakage,
- chemical instability,
- cavitation,
- temperature instability,
- wear,
- material distortion or misalignment.

Contamination Control. Contamination of the lubricant or hydraulic with leads directly to reduced component and machine life. For example, the Timken Bearing Company report that the effect of water on bearing life is shown on the attached graph. Notice that reducing water contamination from 0.01% (100 ppm) to 0.0025% or (25 ppm) increases bearing life by a factor of 2.5 times!



The SKF Bearing Company report that if contaminants larger than the clearances between bearing elements are filtered from the system, the bearing can effectively have infinite life!

The British Hydraulics Research Association reports that if the solid particle contamination in an operating system can be reduced from ISO 20 to ISO 15 for particles larger than 5 microns, then machine life will be increased by five times!

Contamination control, for both water and solid particle contamination, is a proven method to extend machine life, and reduce both start up and random failure occurrences.

Target Cleanliness Levels (TCLs) need to be established for both water and for solid particle contamination in lubricant and hydraulic system. The units TCL for water are in percent or ppm. The TCL units for solid particles are typically given as ISO or NAS code values.

In general, high pressure systems (e.g., hydraulics) have much greater sensitivity to small amounts of water and wear debris than low pressure systems (e.g., lubricants). TCLs are set based on the most sensitive component within the system. Filter companies and original equipment manufacturers have published recommended TCL values for particle contamination. The TCLs for water contamination are best set by monitoring plant systems and taking all reasonable steps to minimize moisture in lubricant and hydraulic systems.

Oil Analysis. Analysis of oil for maintenance purposes can be compared to analysis of blood for medical purposes. In both cases the fluid contains valuable information that can be revealed through testing. Sometimes one test gives all the needed information, other times, an entire battery of tests is needed. Some tests are simple and inexpensive. Others are elaborate and expensive. So which tests get run for a particular sample? What instruments are used? What is the purpose?

Addressing these questions beginning with the last, what are the purposes for oil analysis? Just about any test done on new and used lubricants are intended to find out one or more pieces of information about three conditions: (1) the condition of the lubricant, (2) the state of cleanliness (absence of contamination) for the lubricant system, and (3) the health of the oil wetted machinery. A range of tests can be conducted to fully explore every one of these conditions, however it is not practical to do them all on all equipment. So how does one select which test to run and what equipment or method should be used?

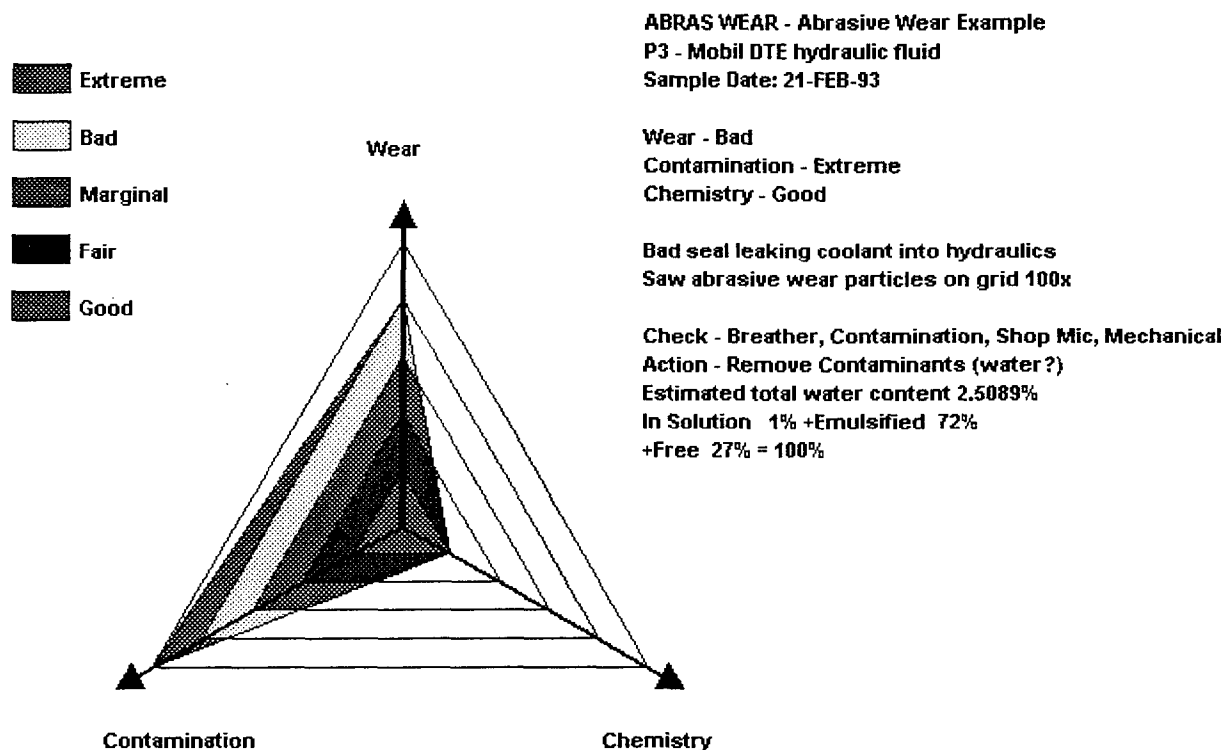
As stated earlier, there are a variety of tests one can perform to measure each of these parameters. The appropriate tests are selected giving consideration to the relative benefit and cost of each.

Almost any lubricant or hydraulic fluid sample can and should be tested on-site by the condition monitoring team. On-site oil analyzers are capable of measuring lubricant quality, solid and liquid contamination, and mechanical wear debris. At the same time, more detailed and comprehensive analyses are available off-site from a qualified fluid analysis laboratory.

Although oil analysis appears to be complex, it really is quite easy to understand. The primary thing that makes it appear difficult is probably confusion over what the numbers mean. The results of oil analysis are in widely different units such as mg-KOH, parts-per-million,

dimensionless index units, absorption at a wave number, mg/L, and many more. A convenient representation has been developed to bring all this complexity back into a simple to recognize diagram. This 3-dimensional representation of all available oil analysis results, whether from an off-site lab or an on site "minilab," is called the "Trivector" and is shown in the following figure.

In this figure, the x-, y- and z-axis each represent chemistry, contamination and wear respectively. Each axis is normalized using the relative alarm levels for each different measurement parameter. Graphic illustration is supported by text and numeric information to give the user a status-at-a-glance understanding for the sample.



On-Site Oil Analysis. In-shop, in-house, and bench-top are all terms that have been used in reference to on-site oil analysis. This form of testing can and should be done by the condition monitoring team. It should be in the same general area of the plant where the people who do vibration analysis, shaft alignment, and balancing are located. On-site oil analysis realizes the following benefits:

- ownership and control,
- immediate results with immediate retest when needed,
- analysis is done by the people who know the most about these machines,
- electronic data with no transfer,
- test more points more often,
- test incoming lubricants, and
- find, fix, and verify problems are fixed all in same day.

The first step in on-site oil analysis requires no special instrumentation. It is as simple as look, smell, touch, and think. The condition monitoring technician or plant oiler who is equipped only with familiarity of the fundamentals of tribology can add significant value to the program.

SKF report that 75% of all bearings fail because of inadequate lubrication and another 24% fail due to irregularities in the environment such as improper installation. Many of these failures can be avoided by looking at fluid sight glasses, and by using the right tools and techniques for handling, storage, and installation of bearings.

Quantifiable and highly sensitive measurements of lubricant properties, contamination levels, and wear conditions are also available through on-site oil analysis. A variety of instruments are designed to provide the plant condition monitoring team with partial to comprehensive analysis capabilities.

- either individual or multi-functional oil analysis instruments capable of quantitatively measuring lubricant degradation, water contamination, and iron wear debris,
- in-shop wear debris analysis tools including a microscope,
- in-shop viscometers to identify misapplication of lubricants and fluid or gas contamination,
- field rugged particle counters to measure particulate contamination, and
- automatic ferrographic instruments suitable for rapid automatic measurement of total iron content.

The best programs typically start small and grow. The best practice, continuous improvement plan should be laid out with the intent of building a "minilab" appropriate for on-site oil analysis. All of the on-site instruments are should operated from the software. This software should have full database and reporting capabilities. Those who use both vibration and oil analysis should expect full integration of these complementary technologies within a single data structure and within the same software.

Off-Site Oil Analysis. Fluid analysis and consulting services should be obtained from an qualified industrial fluid analysis laboratory. This section outlines the *minimum* capabilities for a suitable industrial fluid analysis laboratory including:

- Spectrometric oil analysis (SOA) including rotrode spectroscopy,
- Viscometry at 40 C and 100 C,
- Infrared Spectroscopy (FTIR),
- Wear debris analysis,
- Total Acid Number (TAN),
- Water by Karl Fisher, and
- Particle counting with true size distribution.

Measuring Performance – Typical Metrics. Financial metrics are needed to gage the effectiveness of a tribology program. The first step is to establish a baseline for comparison in future years. This is essential in some plants for the long term success of the tribology program. This is because the marginal savings from year to year reduces as the program approaches industry benchmark status. All too often, management loses sight of the major savings achieved when the tribology program was first implemented. Then in lean years, budget cuts take short-term savings, allowing the plant to slip back into poor tribology practices and associated costs.

Measure Equipment Failure Avoidance. This category typically accounts for 70% of the total tribology program cost savings. Two approaches are used to measure savings from equipment failure avoidance: (1) case-by-case, and (2) class-by-class. The total cost savings for equipment failure avoidance is the sum of these two, taking care not to double count.

Measure Case-by-Case. These savings are documented on a case-by-case basis using CSI's compile case histories. Tribology equipment failure avoidance case histories are commonly triggered by one of two events: extreme wear condition or extreme lubricant contamination from water, coolant, or process materials detected in the lubricant.

For example, a rotary vane mechanical pump costs \$16,000 to replace. This particular pump is water cooled. On-site analysis revealed extreme amounts of water and large wear debris in the oil. Unnoticed, it is reasonable to assume that this pump would have failed under this condition. Pump seals and bearings were replaced at a cost of \$1,000. Since a backup pump was available and operational, no credit is taken for loss of production. Cost avoidance in this case is $\$16,000 - \$1,000 = \$15,000$.

Measure Class-by-Class. These savings are documented on a class-by-class basis through grouping similar equipment into class groups. It is suggested that the condition maintenance team identify the 5 most common classes of equipment in the plant. Do not attempt to group all plant equipment into these classes, only group the same kinds.

For example a power plant uses 27 similar coal pulverizers which were grouped together into one class. Maintenance and repair histories for these pulverizers can then be studied and trended. In this particular case, pulverizers followed scheduled maintenance and overhaul. Typical overhaul of the main bearings cost \$10,000. Unscheduled failures, or breakdown occurred at the rate of 3 or 4 per year.

A tribology condition monitoring program was implemented such that overhauls were done on condition rather than on schedule. Statistical alarms were used including all 27 pulverizers. Those falling at the upper end of the statistical range (e.g., those with the highest 20%) received corrective actions. Those with high Corrosion, OilLife, and Contaminant indexes received oil changes and seals were inspected and replaced as needed. Those with highest ferrous index values were torn down for overhaul maintenance.

The number of breakdowns dropped to less than 1 per year and the amount spent on overhaul was also reduced. The pulverizer class achieved a total cost savings of \$240,000 in the first year after these practices were implemented.

Measure the Cost of Proactive Maintenance. This category accumulates the actual costs for proactive maintenance measures. These actions are intended to extend machine life. Therefore, the expenditure occurs in different periods than the resulting savings. In fact, the actual savings from proactive maintenance measures become very difficult to track. Nonetheless, the expenditures are able to be categorized and historically tracked:

- cost of improved filtration,
- cost of root cause failure analysis, and
- cost of other root cause elimination.

Measure the Cost of Lube Procurement and Material Handling. This category typically accounts for 25% of the total tribology program cost savings. It involves accounting for the total investment procurement and handling of lubricants and hydraulics.

- purchase fluids,
- store fluids,
- transfer fluid into machines using filter cart,
- remove fluid from machines,
- recycle fluids, and
- dispose of spent fluids.

Lubricant consolidation is an area that the condition monitoring team, assisted by consultation, can assist the procurement organization in achieving significant savings. Not only are savings available through improved purchasing power, there are less lubricants to inspect and inventory; and the problems associated with misapplication of lubricant are greatly reduced. In one case, a major steel manufacturer successfully consolidated 1400 different lubricant types to less than 100. This process was deliberate and took four years to achieve. It resulted in several million dollars savings per year.

Procurement of quality lubricants is an area that the plant condition monitoring team needs to be involved with. First, the purchase order needs to specify minimum lubricant condition properties and tests as needed to assure performance. These may include setting Target Cleanliness Levels (TCLs). However, a TCL requirement imposed on the supplier may cause the cost to be higher than filtering to acceptable TCLs at the plant. When purchasing large quantities of lubricant in bulk, it is advisable to require the supplier to deliver the shipment with a oil analysis report. Do not accept the shipment unless the driver arrives with this analysis in-hand. This is important because once the fluid is in the plant, it is too late to do much about it.

Add to this the requirement to take two oil samples at the time the lubricant is filled into the plant reservoir. One of these goes back to the supplier, the other is sent to the plant fluid analysis laboratory.

Measure the Cost of Plant Power Usage. Contamination control and proper selection of lubricant viscosities can have an impact on plant power usage. This is another area in which consultation is required. One object here is to find the areas in which systems are operating with higher than required viscosity grades. High viscosity means high drag, increased power consumption, and increased fluid temperatures.

Since viscosity is strongly dependent on temperature, the condition monitoring team must identify the operating temperatures for high power machines. When the viscosity is above that required to support the lubrication regimes in the selected machinery, then reduce grades. At this point it is necessary to once again measure temperature since power loss is reduced due to viscosity.

Support and Implementation of Best Practices. It is advisable to take advantage of audits, start-up assistance, consultation, and training services which are available to support the plant tribology program.

Audit to Review Needs. Periodic auditing to review specific needs within the plant is suggested for best practice. CSI or other plants can be involved in this process. The CSI audit addresses all of the topics listed in this report. Each audit should compare this plant with plants identified as industry benchmark (e.g., those setting the highest standards for tribology practices). The audit report includes an assessment of performance and recommends activities for continuous improvement.

Continuous Improvement. After the initial audit, a continuous improvement plan is drafted. The plan includes objectives to be achieved during the following 24 months. Then quarterly reviews are conducted to measure progress. At each annual review, the plan is extended for another year. Each quarterly review is summarized in a status report to the maintenance manager and to the plant manager. The report includes available financial metrics (see section 3).

Network the Process. Communication is a valuable asset in successful program implementation. Effectiveness is improved by frequent exchange of tribology information. The condition monitoring maintenance team needs to be the central point of contact within the plant.

- between maintenance, production, and other departments (e-mail and periodic meetings),
- between different plant maintenance departments (e-mail and periodic meetings),
- with suppliers of on-site oil analysis equipment (phone and user group meeting),
- with tribology auditing, consulting, and training service suppliers (on-site quarterly audits plus scheduled training),
- with the fluid analysis laboratory (phone and electronic link via modem), and
- with suppliers of lubricants, hydraulic fluids, and filtration products (phone and on-site consultation).

Ensure the Process is Evergreen. The best way to ensure that tribology best practices remain "evergreen" is to document where the program started, where it is going, and what progress has

been made. Keep it visible. Keep it improving. The financial metrics (section 3) and the periodic audits (section 8) can help achieve both of these. People make success, not programs. Identify the people who are part of the tribology program effort. Train them, give them responsibility, and measure their progress. Most important, appoint a single person to be responsible for the total tribology program within the plant. Empower this person to build the program in accordance with management established objectives.

Conclusion. Tribology, which is the science of friction, lubrication and wear, is a fundamental to all mechanical systems. Production and profits can either benefit or be hurt by the approach that is taken to tribology. Industrial plants that are the benchmark performers in tribology for their industry take credit for large savings each year. These savings can result directly from oil analysis information as it reveals hidden information about machine wear condition, lubricant chemistry, or lubricant contamination. They can also result from effective lubricant procurement, storage, handling, and disposal practices, as well as root cause failure analysis, and resulting corrective measures. Probably the most important aspect of an effective tribology program is the way it is implemented by people. Do they understand tribology information? Do they know what to do with that information? Do they take ownership for the program and its results? Do they have management support? When the answers to these questions are all "yes," then the plant is on the way to benchmark status.

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